Thermal right-handed sneutrino dark matter in the Next-to-MSSM

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Abstract. The right-handed sneutrino is a viable WIMP dark matter candidate within the context of the Next-to-MSSM through the inclusion of a new singlet superfield with direct coupling to the singlet Higgs. Sneutrinos within a mass-range of 5-200 GeV can reproduce the correct dark matter relic abundance while not being excluded by current direct searches, and for natural values of the input parameters. Some interesting features regarding collider phenomenology are also pointed out.

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Introduction. The minimal supersymmetric extension of the standard model (MSSM) contains two possible candidates for WIMP dark matter (DM), the neutralino and the (left-handed) sneutrino [1]. The neutralino is a popular and widely studied candidate. On the contrary, the (left-handed) sneutrino in the MSSM has a sizable coupling to the Z boson and either annihilates too rapidly (resulting in a very small relic abundance) or gives rise to a too large scattering cross-section off nuclei (being excluded by direct searches of DM) [2]. Several attempts have been made to solve this conundrum through the reduction of the sneutrino coupling with the Z boson. This can be achieved by introducing a mixture of left- and right-handed sneutrino states [4, 5, 6], however a significant mixture is only possible if some particular supersymmetry breaking with an unnaturally large trilinear term [4] is adopted. Another possibility is to consider a pure right-handed sneutrino [7, 8, 9, 10]. These cannot be thermal relics, since their coupling to ordinary matter is extremely reduced by the neutrino Yukawa coupling [7, 8, 9], unless they are somehow coupled to the observable sector, for example via an extension of the gauge [10, 11] or Higgs [13, 14, 15, 16, 18] sectors. As a final possibility, non-LSP right-handed sneutrino DM was also proposed [17].

Extending the MSSM Higgs sector is particularly appealing in order to address the so-called "μ problem" [12]. The next-to-minimal supersymmetric standard model (NMSSM) offers a simple solution by introducing a singlet superfield S and promoting the bilinear $\mu H_1 H_2$ term to a trilinear coupling $\lambda S H_1 H_2$. After radiative electroweak symmetry-breaking (REWSB), S develops a vacuum expectation value (VEV) and provides an effective term, $\mu = \lambda \langle S \rangle$.

With this motivation, we study an extension of the NMSSM in which a singlet scalar right-handed neutrino superfield, N, is included to obtain non-vanishing neutrino Majorana masses with a low scale see-saw mechanism. The superpotential reads [15, 18] $W = W_{\mathrm{NMSSM}} + \lambda_N SNN + y_N L \cdot H_2 N$, and contains a new trilinear coupling between the singlet superfields S and N and the corresponding Yukawa terms. The terms NNN and

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SSN are gauge invariant but violate R-parity and thus are not included. After REWSB the Higgs fields take non-vanishing VEVs, $(v_{1,2}, v_s) = (\langle H_{1,2}\rangle, \langle S\rangle)$, and a Majorana mass term is generated, $M_N = 2\lambda_N v_s$. Masses for left-handed neutrinos are obtained via a see-saw mechanism, $m_{\nu_L} = y_N^2 v_2^2 / M_N$, implying small Yukawa couplings, $y_N \lesssim \mathcal{O}(10^{-6})$.

Our model contains three new inputs with respect to the NMSSM parameter space, namely the coupling λ_N, the associated soft trilinear term, A_{λ_N}, and the soft right-handed sneutrino mass, $m_{\tilde{N}}$. A crucial feature of this scenario is the existence of direct couplings of the right-handed sneutrino to Higgses and neutralinos. These emerge through the term $\lambda_N SNN$ in the superpotential, since the singlet and singlino components of S mix with the CP-even Higgs bosons and neutralinos, respectively. The strength of the interaction is therefore dependent on the values of λ_N and A_{λ_N}. The coupling between the lightest right-handed sneutrino, $\tilde{N}_1$ and a Higgs boson, H_i^0, determines most of the sneutrino phenomenological properties, and reads

$$C_{H_i^0 \tilde{N}_1 \tilde{N}_1} = \frac{2\lambda\lambda_N M_W}{\sqrt{2}g}\left(\sin\beta S^1_{H_i^0} + \cos\beta S^2_{H_i^0}\right) + \left[\left(4{\lambda_N}^2 + 2\kappa\lambda_N\right) v_s + \frac{\lambda_N A_{\lambda_N}}{\sqrt{2}}\right] S^3_{H_i^0} \, ,$$

where $S^j_{H_i^0}$ ($j = 1,2,3$) are the elements of the Higgs diagonalisation matrix.

Thermal production. The right-handed sneutrino coupling to the Higgs sector provides tree-level interactions with ordinary matter. For adequate values of λ_N (and A_{λ_N}) these couplings would be of electroweak scale, thereby making it a WIMP candidate. The analysis of the NMSSM phenomenology is performed with the `NMHDECAY` 2.0 code [19], based on which we have built a set of routines which numerically calculate the sneutrino spectrum and relic density. The sneutrino annihilation cross section is extremely sensitive to the structure of the Higgs sector, but there are general features which are easy to understand.

- The coupling λ_N determines the overall scale of the annihilation cross section. Notice that λ_N only affects the right-handed neutrino and sneutrino masses and does not alter the rest of the NMSSM spectrum.
- Annihilation into $H_i^0 H_j^0$ and $A_a^0 A_b^0$ are among the most effective channels. The flexibility of the Higgs sector of the NMSSM make this possibility very versatile. Very light CP-even and CP-odd Higgses are possible (as long as they are singlet-like), making these channels available for a wide range of sneutrino masses. In particular, very light sneutrinos can thus reproduce the correct relic abundance.
- Another relevant contribution to the total annihilation cross section is due to the annihilation into a pair of right-handed neutrinos, NN.
- Finally, for all the possible annihilation products there is always a contribution coming from s-channel CP-even Higgs exchange. This implies that all of them are subject to a resonant effect when $2m_{\tilde{N}_1} \approx m_{H_i^0}$, for $i = 1,2,3$.

Fig. 1 shows the sneutrino relic abundance as a function of the sneutrino mass, $m_{\tilde{N}_1}$, for a representative example in the NMSSM parameter space described in Ref. [18], with $\lambda_N = [0.05, 0.1]$, $m_{\tilde{N}} = [0, 200]$ GeV, and $A_{\lambda_N} = 250$ GeV. The relic abundance increases as λ_N decreases due to the reduction in $C_{H_i^0 \tilde{N}_1 \tilde{N}_1}$. The large suppression on the Higgs

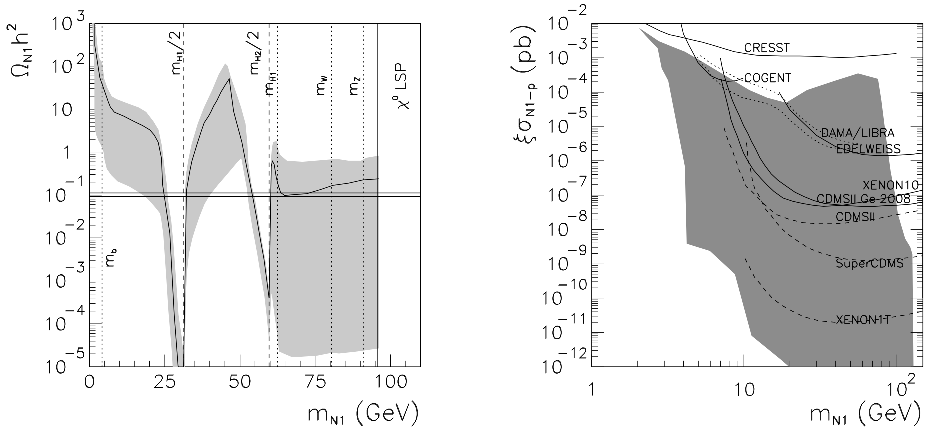

FIGURE 1. Left) Theoretical predictions for the sneutrino relic density as a function of $m_{\tilde{N}_1}$ for a scan in the parameters corresponding to case A) in Table 1 of Ref. [18]. Vertical dashed lines indicate the resonant annihilation for $2m_{\tilde{N}_1} \approx m_{H_i^0}$, whereas vertical dotted lines indicate the opening of the various channels. Right) Theoretical prediction for $\sigma^{\rm SI}_{\tilde{N}_1-p}$ as a function of $m_{\tilde{N}_1}$ for a scan in the NMSSM parameter space.

resonances is clearly evidenced. The correct relic density can be obtained with natural values of λ_N and without the need of resonant effects. For example, when annihilation into scalar Higgses is possible ($m_{\tilde{N}_1} > 70$ GeV in this example), one needs $\lambda_N \sim 0.06$.

Direct detection. The direct detection of right-handed sneutrinos could take place through their elastic scattering with nuclei inside a DM detector. There is only one diagram contributing to this process, namely, the t-channel exchange of neutral Higgses (the exchange of a Z boson is largely suppressed by the neutrino Yukawa squared). The total spin-independent sneutrino-proton scattering cross section yields

$$\sigma^{\rm SI}_{\tilde{N}_1-p} = \frac{m_p^4}{\pi(m_p+m_{\tilde{N}_1})^2}\left(\sum_{q_i=u,d,s} f^p_{Tq_i}\sum_{j=1}^{3}\frac{C_{H_j^0\tilde{N}_1\tilde{N}_1}Y_{q_i}}{m^2_{H_j^0}m_{q_i}} + \frac{2f^p_{TG}}{27}\sum_{q_i=c,b,t}\sum_{j=1}^{3}\frac{C_{H_j^0\tilde{N}_1\tilde{N}_1}Y_{q_i}}{m^2_{H_j^0}m_{q_i}}\right)^2,$$

where Y_{q_i} is the corresponding quark Yukawa coupling and $f^p_{Tq_i}$ and f^p_{TG} are the hadronic matrix elements. The sneutrino detection cross section is extremely dependent on the features of the Higgs sector of the model. In particular, $\sigma^{\rm SI}_{\tilde{N}_1-p}$ becomes larger when the sneutrino-sneutrino-Higgs coupling increases (which can be achieved by enhancing λ_N or with large values for $|A_{\lambda_N}|$), and when the Higgs mass becomes smaller.

The theoretical predictions for $\sigma^{\rm SI}_{\tilde{N}_1-p}$ are represented as a function of the sneutrino mass on the right hand-side of Fig. 1 for a wide scan in the NMSSM parameter space as described in Ref. [18]. The right-handed sneutrino in our model is not yet excluded by direct searches for DM, and the predicted $\sigma^{\rm SI}_{\tilde{N}_1-p}$ lies within the reach of projected experiments for some regions in the parameter space.

Collider phenomenology. Apart from the usual signals of missing transverse momentum, an attractive possibility is the production of right-handed neutrinos in the decay of either a Higgs or a neutralino NLSP. The right-handed neutrino would be long-lived and decay, through the tiny mixing with the left-handed component, into a W boson and a charged lepton, giving rise to a displaced vertex which could be observed. Furthermore, a singlet-like Higgs boson can decay into pair of LSP right-handed sneutrinos and a pair of right-handed neutrinos (missing momentums and long-lived particles), a very characteristic signal. There is a related consequence, namely the invisible decay of the Higgs boson, since the right-handed sneutrino interacts with the CP-even Higgs through the coupling $C_{H_i^0 \tilde{N}_1 \tilde{N}_1}$.

Conclusions. The right-handed sneutrino is a viable thermal WIMP candidate for DM in an extended NMSSM with a new singlet superfield, N. A direct coupling between N and the Higgs provides a sufficiently large annihilation cross section sneutrino and a scattering cross-section off nuclei which is not excluded by current direct DM searches. Sneutrinos within a mass-range of 5-200 GeV can reproduce the correct relic abundance and the prospects for their direct detection can be within the range of future detectors.

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